

Effect of Cutting Parameters on Cutting Force and Surface Roughness of Aluminium Components using Face Milling Process - a Taguchi Approach

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Abstract: Aluminum is used excessively in the modern world and the uses of the metals are extremely diverse due to its many unusual combinations of properties. They have been widely used in industries, especially aerospace industries due to their attractive mechanical and chemical properties. However, machining of Aluminium results in good surface finish at the expense of tooling cost. This study investigates the optimum parameters that could produce significant good surface finish and optimum cutting force thereby reducing tooling cost. It employs the Taguchi design method to optimize the surface roughness quality and cutting force in a Computer Numerical Control (CNC). The milling parameters evaluated are cutting speed, feed rate and depth of cut. An $L_9(3^4)$ orthogonal array, signal-to-noise (S/N) ratio and analysis of variance (ANOVA) are employed to analyze the effect of these cutting parameters. The analysis of the result indicates that the optimal combination for low resultant cutting force and good surface finish are high cutting speed, low feed rate and low depth of cut. The study shows that the Taguchi method is suitable to solve the machining problems with minimum number of trials as compared with a full factorial design.

I. INTRODUCTION

Robust design is an engineering methodology for obtaining product and process conditions, which are minimally sensitive to the various causes of variation to produce high-quality products with low development and manufacturing costs [1]. Taguchi's parameter design is an important tool for robust design. It offers a simple and systematic approach to optimize design for performance, quality and cost. Two major tools used in robust design or Taguchi design are [1–6]:

- Signal to noise ratio, which measures quality with emphasis on variation, and
- Orthogonal arrays, which accommodate many design factors simultaneously.

When a critical quality characteristic deviates from the target value, it causes a loss [2]. Continuously pursuing variability reduction from the target value in critical quality characteristics is the key to achieve high quality and reduce cost.

The successful applications of Taguchi methods by both engineers and statisticians within British industry have led to the formation of UK Taguchi Club [4]. Taguchi's approach is totally based on statistical design of experiments [1], and this can economically satisfy the needs of problem solving and product/process design optimization [5]. By applying this technique one can significantly reduce the time required for experimental investigation, as it is effective in investigating the effects of multiple factors on performance as well as to study the influence of individual factors to determine which factor has more influence, which less [1,6]. Some of the previous works that used the Taguchi method as tool for design of experiment in various areas including metal cutting are listed in Refs. [7–10].

Numerous roughness height parameters such as average roughness, smoothing depth, root mean square and maximum peak-to-valley height can be closely correlated. This study uses average roughness for the characterization of surface roughness, due to the fact that it is widely adopted in the industry for specifying the surface roughness. Mital M. Mehta [13] has conducted a survey of the previously developed surface roughness prediction models and factors influencing the surface roughness. He has found that most of the surface roughness prediction models have been developed for steels.

This paper describes a case study on face milling parameters at three levels each. The main objective is to find a combination of milling parameters to achieve low cutting force and surface roughness.

II. MATERIAL AND METHODS

A Material

Aluminum is a soft, lightweight, malleable metal with appearance of a silver-white metal obtained from bauxite. The appearance may range from silvery to dull gray, depending on the surface roughness. The yield strength of pure aluminum is 7–11 MPa, while aluminum alloys have yield strengths ranging from 200 MPa to 600 MPa. Aluminum has about one-third the density and stiffness of steel. It is ductile, and can be easily machined, cast, and extruded. Aluminum is a good thermal and electrical conductor, by weight better than copper. Aluminum is capable of being a superconductor, with a superconducting critical temperature of 1.2 Kelvin and a critical magnetic field of about 100 gauss.

B Design of experiment

Design of experiment is the powerful analysis tool for modeling and analyzing the influence of the control factors on the performance output. The most important stage in the design of experiment lies in the selection of the control factors. The operating conditions, under which measurement of cutting force carried out, are given in Table 1

The Taguchi method, which is effective to deal with responses, is influenced by multi-variables [16]. This method drastically reduces the number of experiments that are required to model the response function compared with the full factorial design of experiments. The Taguchi technique is devised for process optimization and identification of optimal combination of the factors for a given response. This technique is divided into three main phases, which encompasses all experimentation approaches. The three phases are (1) the planning phase (2) the conducting phase and (3) the analysis phase. This technique creates a standard orthogonal array to accommodate the effect of several factors on the target value and defines the plan of experiments. The experimental results are analyzed using analysis of means and variance to study the influence of factors.

Three parameters, viz., Feed Rate, Spindle Speed and Depth of Cut each at three levels, are considered in this study in accordance with $L_9(3^4)$ orthogonal array design. The plan of the experiment is as follows: the first column is assigned to the Feed Rate (A), the second column to the Spindle Speed (B), the fourth column to the Depth of Cut (C).

TABLE I
Control factors and their levels

Parameters	Level 1	Level 2	Level 3
Feed Rate(mm/min)	400	800	1600
Spindle Speed(rpm)	1300	1800	2600
Depth of cut(mm)	0.7	1.2	1.7

The experimental observations are transformed into signal-to-noise (S/N) ratio. There are several S/N ratios available depending on the type of characteristic, which can be calculated as logarithmic transformation of the loss function. For lower is the better characteristic, the following equation is used.

$$\frac{S}{N} = -10 \log_{10} \frac{1}{n} (\sum y^2) \tag{1}$$

Where ‘n’ is the number of observations, and ‘y’ the observed data. “Lower is the better” (LB) characteristic, with the above S/N ratio transformation, is suitable for minimization of average cutting force measured along X, Y and Z axes.

C Surface roughness evaluation

There are various simple surface roughness amplitude parameters used in industry, such as roughness average (Ra), root-meansquare (rms) roughness (Rq), and maximum peak-to-valley roughness (Ry or Rmax), etc. Since Ra and Rq are the most widely used surface parameters in industry, Ra was selected to express the surface roughness in this study. The average roughness (Ra) is the area between the roughness profile and its mean line, or the integral of the absolute value of the roughness profile height over the evaluation length (Fig.1). The Ra is specified by the following equation:

$$Ra = \frac{1}{L} \int_0^L |Y(x)| dx (\mu m) \tag{2}$$

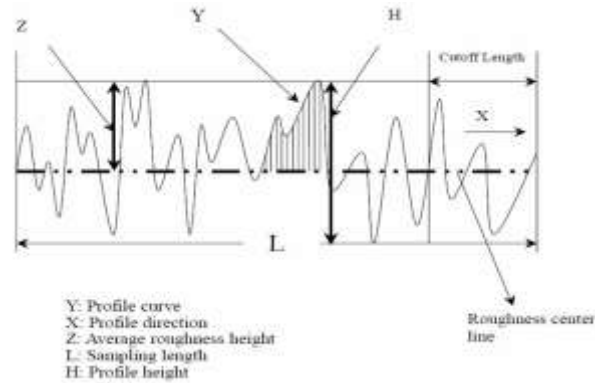


Fig.1. Surface roughness profile (Chen and Yang, 2001).

A Machining parameter

To improve the quality of surface roughness of Aluminium alloys and processes with minimum cost and time constraints, the Taguchi parameter design techniques are applied in design of experiment (DOE). Minimum surface roughness average (Ra) is carried out since the value represents better or improved surface roughness. Therefore, a smaller-the-better method is implemented in this experiment [14]. The controllable parameters are selected because of their potential effects on surface roughness performance in face milling operations. The parameters feed rate (A), cutting speed (B) and the depth of cut (C) used as control parameters to measure responses for surface roughness and signal-to-noise ratio can be calculated to determine the optimum cutting condition [15].

B Experimental Setup

BFW Agni BMV 45 T20 CNC vertical axis milling machine is used for the machining of the Aluminium components. The milling cutter used for experimentation is SECO R220.69-12 grade. The tool holder used for experimentation was BT 40 grade. Face Milled components are shown in Figure 2. A Mitutoyo Surf test SJ-301 Profilometer was used to measure surface roughness (Ra) of the machined components. Variation in the cutting force during the machining is calculated using the spindle power. The average cutting force measured along X, Y and Z axes called the F_x , F_y and F_z respectively.



Fig.2. Face milled Aluminium work pieces.

III. RESULTS AND DISCUSSIONS

• Analysis of Experimental Results

The experimental data for cutting force and roughness is reported in the Table 2. From Table 2 the overall mean for the S/N ratio of the cutting force F_x , F_y , F_z and the roughness are found to be -54.32db, - 51.59 db and 8.34 db respectively. The analyses of the experimental data are carried using the software MINITAB 15 specially used for design of experiment applications.

• Analysis of S/N Ratio

Figs. 3-5 showed the main effects plot for S/N ratios. The level of a factor with the highest S/N ratio was the optimum level for responses measured. From the S/N ratio analysis in Figs. 1-3, the optimal machining conditions were 400 mm/min feed rate (level 1), 2600 rpm spindle speed (level 3) and 0.7 mm depth of cut (level 1) for cutting force F_x , F_y and F_z .

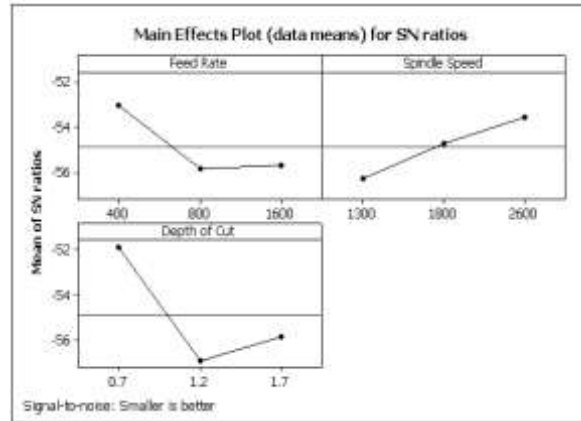


Fig.3. S/N ratio values for F_x

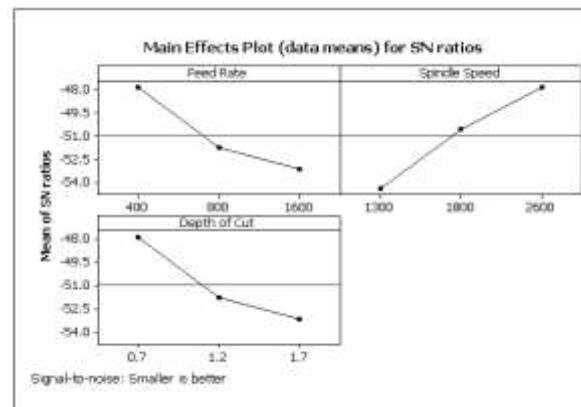


Fig.4. S/N ratio values for F_y

TABLE II
EXPERIMENTAL RESULTS

Feed Rate (A)	Spindle Speed (B)	Depth of Cut (C)	$F_x(N)$	S/N Ratio	$F_y(N)$	S/N Ratio	$F_z(N)$	S/N Ratio	$R_a(\mu m)$	S/N Ratio
400	1300	0.7	392	-51.8657	235.2	-47.4287	490	-53.8039	0.18	14.8945
400	1800	1.2	588	-55.3875	274.4	-48.7677	490	-53.8039	0.11	19.1721
400	2600	1.7	392	-51.8657	235.2	-47.4287	490	-53.8039	0.39	8.1787
800	1300	1.7	862.4	-58.7142	784	-57.8863	637	-56.0828	0.48	6.3752
800	1800	0.7	392	-51.8657	274.4	-48.7677	490	-53.8039	0.23	12.7654
800	2600	1.2	705.6	-56.9712	274.4	-48.7677	588	-55.3875	0.3	10.4576
1600	1300	1.2	823.2	-58.3101	784	-57.8863	637	-56.0828	0.55	5.1927
1600	1800	1.7	705.6	-56.9712	509.6	-54.1446	686	-56.7265	0.31	10.1728
1600	2600	0.7	392	-51.8657	235.2	-47.4287	539	-54.6318	0.44	7.1309

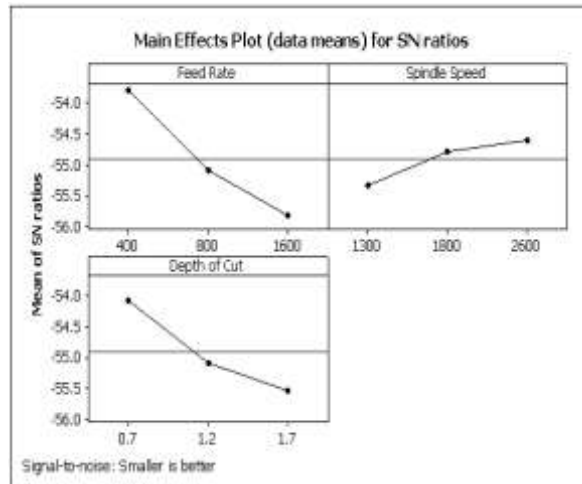


Fig.5. S/N ratio values for F_z

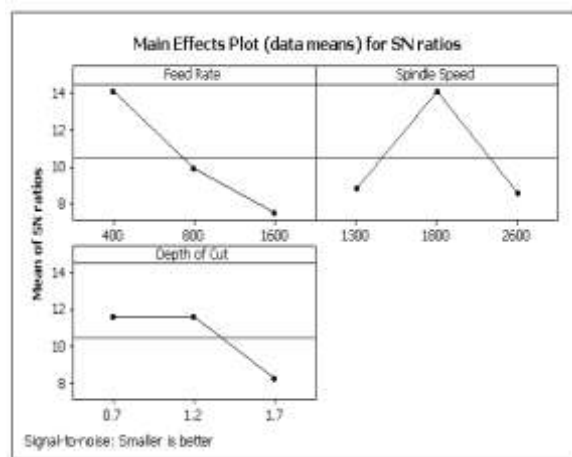


Fig.6. S/N ratio values for Surface Roughness

From Fig.6, the optimal machining conditions were 400 m/min feed rate (level 1), 1800 rpm spindle speed (level 2) and 0.7 mm depth of cut (level 1) respectively for surface roughness.

- **Analysis of Variance (ANOVA)**

ANOVA was used to determine the significant parameters influencing the surface roughness and force components in the milling of Aluminium specimen. Tables 3-6 showed the summary of S/N values and ANOVA results for cutting force F_x , F_y , F_z and surface roughness, respectively. In this study, analysis was at a level of significance 5%. In order to understand a concrete visualization of impact of various factors effect on the output performance, it is desirable to develop analysis of variance (ANOVA) table to find out the order of significant factors. From Table 3 one can observe that the depth of cut ($p=0.072$) has greater static influence of 58.76% followed by feed rate ($p=0.179$) has an influence of 20.99% and spindle speed ($p=0.226$) has an influence of 15.65% on cutting force F_x .

From Table 4 one can observe that the spindle speed ($p=0.046$) has greater static influence of 40.87% followed by feed rate and depth of cut ($p=0.064$) has an influence of 28.58% on cutting force F_y . From Table 5 one can observe that the feed rate ($p=0.120$) has greater static influence of 55.27% followed by depth of cut ($p=0.202$) has an influence of 29.76% and spindle speed ($p=0.502$) has an influence of 7.45% on cutting force F_z .

TABLE III
SUMMARY OF S/N VALUES AND ANOVA RESULTS FOR FX

Factors	Degrees of Freedom DF	Average S/N Values			Sum of Square	Mean Square	F	P	Percentage of Contribution (%)
		Level 1	Level 2	Level 3					
Feed Rate	2	-53.04	-55.85	-55.72	15.079	7.540	4.58	0.179	20.99
Spindle Speed	2	-56.30	-54.74	-53.57	11.245	5.622	3.42	0.226	15.65
Depth of Cut	2	-51.87	-56.89	-55.85	42.197	21.098	12.82	0.072	58.76
Error	2				3.292	1.646			4.60
Total	8				71.812				100

S = 1.28289 R-Sq = 95.42% R-Sq (adj) = 81.67%

TABLE IV
SUMMARY OF S/N VALUES AND ANOVA RESULTS FOR FY

Factors	Degrees of Freedom DF	Average S/N Values			Sum of Square	Mean Square	F	P	Percentage of Contribution (%)
		Level 1	Level 2	Level 3					
Feed Rate	2	-47.88	-51.81	-53.15	45.133	22.566	14.51	0.064	28.58
Spindle Speed	2	-54.40	-50.56	-47.88	64.539	32.270	20.74	0.046	40.87
Depth of Cut	2	-47.88	-51.81	-53.15	45.133	22.566	14.51	0.064	28.58
Error	2				3.111	1.556			1.97
Total	8				157.916				100

S = 1.24724 R-Sq = 98.03% R-Sq (adj) = 92.12%

TABLE V
SUMMARY OF S/N VALUES AND ANOVA RESULTS FOR FZ

Factors	Degrees of Freedom DF	Average S/N Values			Sum of Square	Mean Square	F	P	Percentage of Contribution (%)
		Level 1	Level 2	Level 3					
Feed Rate	2	-53.80	-55.09	-55.81	6.2185	3.1092	7.36	0.120	55.27
Spindle Speed	2	-55.32	-54.78	-54.61	0.8379	0.4190	0.99	0.502	7.45
Depth of Cut	2	-54.08	-55.09	-55.54	3.3478	1.6739	3.96	0.202	29.76
Error	2				0.8450	0.4225			7.52
Total	8				11.2491				100

S = 0.649991 R-Sq = 92.49% R-Sq (adj) = 69.95%

From Table 6, one can observe that, the feed rate (p=0.188) has greater static influence of 41.26% followed by spindle speed (p=0.213) has an influence of 35.21% and depth of cut (p=0.406) has an influence of 13.96% on surface roughness.

TABLE VI
SUMMARY OF S/N VALUES AND ANOVA RESULTS FOR ROUGHNESS

Factors	Degrees of Freedom DF	Average S/N Values			Sum of Square	Mean Square	F	P	Percentage of Contribution (%)
		Level 1	Level 2	Level 3					
Feed Rate	2	14.082	9.866	7.499	66.712	33.356	4.32	0.188	41.26
Spindle Speed	2	8.821	14.037	8.589	56.937	28.469	3.69	0.213	35.21
Depth of Cut	2	11.597	11.607	8.242	22.580	11.290	1.46	0.406	13.96
Error	2				15.447	7.724			9.57
Total	8				161.677				100

S = 2.77916 R-Sq = 90.45% R-Sq (adj) = 61.78%

IV. CONCLUSION

This study discussed the application of Taguchi experimental method for investigating the influence of milling parameters on cutting force and surface roughness during milling of Aluminum. In the milling experiments, different cutting speed, feed rate and depth of cut were utilized. The level of importance of the machining parameters on the cutting force and surface roughness was determined by ANOVA. Based on this study, the following conclusions can be drawn for the milling conditions:

1. The optimal machining conditions were 400 mm/min feed rate (level 1), 2600 rpm spindle speed (level 3) and 0.7 mm depth of cut (level 1) for cutting force F_x , F_y and F_z .
2. The optimal machining conditions were 400 m/min feed rate (level 1), 1800 rpm spindle speed (level 2) and 0.7 mm depth of cut (level 1) for surface roughness.
3. The depth of cut had a greater static influence followed by feed rate and spindle speed on cutting force component F_x .
4. The spindle speed had greater static influence followed by feed rate and depth of cut on cutting force component F_y .
5. The feed rate has greater static influence followed by depth of cut and spindle speed on cutting force component F_z .
6. The feed rate has greater static influence followed by spindle speed and depth of cut on surface roughness.

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